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Review of Aluminum Foam Applications in Architecture

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ABSTRACT

The application of aluminum foam materials is increasing rapidly due to the high demand during the last decades. This research presents an overview of the characteristics and architectural applications of aluminum foam materials. Moreover, it represents the most relevant properties, in particular, physical and mechanical aspects and figures out the prospects and growth rate of these materials in architectures by considering the economic benefits. Besides, based on these specific characterizations, the most valuable applications along with advantageous in architectural works are discussed.

1. Introduction

The applications of aluminum foam materials have been widely invariant since the last decades. The first commercial product of metal foam was manufactured by Shinko Wire in Amagasaki, Japan in the 1980s; where the metallic foam was provided through the process called Alporas (Miyoshi et al, 2000). This name was assigned to the foam produced to the corresponding process, and it was patented first in 1987 in the USA. In the 1990s, a new approach by Alcan International Limited (Montreal, Canada), and Norsk Hydro (Oslo, Norway) founded. In this manufacturing method of aluminum foaming, in the prepared melted ceramic, air bubbles are interjected, such as aluminum oxides to solidify for producing foams with no further need of processing. Nowadays, the process is in use of Cymat which is located in Mississauga, Canada. Table 1 represents some of the products and applications of the major metal foam manufactures in the world (Rajak et al, 2017) (Ashby et al, 2000).

Table 1.
The major metal foam producing companies

Company	Products and/or Applications
Alantum (Korea)	Alloy Foam Emission Control Solutions (Particulate Oxidation Catalysts, Diesel Particulate Filters, etc.)
Aluinvent Inc. (Hungary)	High Strength Al-foams
Alulight (Austria)	Al-foams via Powder Route
Alusion (Canada)	Aluminum Foam Plates
Alveotec (France)	Al-foam by Foundry Route
American Elements (U.S.A.)	Metallic & Ceramic Foams with High Purity Al-foam
China Beihai Building Material Co., Ltd. (China)	Aluminum Foam (with Marble) Panels, Blocks, and Sandwiches via Alporas Route

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Alupor (Russia)	Porous Aluminum by Reproduction Casting for an Ample Range of Applications like Sound Insulation, Filtration, Sensors Protection, Impact Absorption, Aeration
Corex Honeycomb (U.K.)	Aluminum Honeycomb Core (Various Applications)
Cymat Technologies Ltd. (Canada)	Stabilized Aluminum Foam (SAF), Al-foam Products with Gas Injection Method
ERG Aerospace Corporation (U.S.A.)	Metal Sponges with Open-cells
EXXENTIS Ltd. (Switzerland)	Aluminum Foam (Porous) Fabricate via Place Holder Method Using for Filters
FOAMTECH (Korea)	Al-Sandwich and foam Plates Made via Alporas Procedure
Fraunhofer Institute (Germany)	Al-foams and Steel Sandwiches via Powder Metallurgy Method
Havel Metal Foam (Germany)	Series Producer for Aluminum Foam Systems
Hollomet GmbH (Germany)	Cellular Metallic and Ceramic Materials
Integran Technogoies Inc. (Canada)	Metal Foams for Noise and Energy Absorption
Mitsubishi Materials Corporation (Japan)	Open-cell Metal Foams
M-Pore (Germany)	Metal Sponges Casting with Open-cells (Al, Cu, Hard Polymer and Others)
Pohltec Metalfoam GmbH (Germany)	Al-alloy Foam Sandwich (AFS)
Reade Advanced Materials (U.S.A.)	Open-cell Metal Foams by Casting and Electrodeposition from Wide Range of Elements Like Al, C, Pb, Cu, Steel, etc.
Recemat BV (Netherlands)	Open-cell Metal from Al, Ni, Ni-alloys, and Cu
SELEE Corporation (U.S.A.)	Ceramic Foam Filter (CFF)
Ultramet (U.S.A.)	Ceramic Matrix Composite (CMC), Persistent Open-cell Metal Sponges

Metallic foams are widely known because of their particular physical and mechanical characteristics such as high stiffness, very low specific weight, high compression strength together with thermal and acoustic absorption. These novel materials with their specific features absorb the focus of the new industrial development (Banhart, 2005).
In recent years, the potential applications of aluminum foam materials are growing rapidly due to the high demand in different industries from aerospace to lightweight constructions; nevertheless, not all these applications are accessible on the market. We are going to talk specifically about closed-cell aluminum foams, which have a high potential for the market. We will review the properties of these materials in section 2 and then address the existing applications in structural and architectural disciplines in section 3. Moreover, the evolution of metallic foams manufacturing is described properly in the review articles (Banhart and Seeliger, 2008) (Mahadev at al, 2018). Subsequently, the conclusion and prospects are defined in Section 4.

2. Properties

Metallic foams may be classified into two main types of open-cells and closed cells. Here, we are going to present a brief description of the main properties of closed-cell foam materials which are used in architecture and produced by Cymat.
Employing metallic foams are beneficial for lightweight structures based on their strength to weight ratio, along with structural and functional features like collision energy absorption, sound, and heat management. Recently, there are plenty of metals such as Steel, Aluminum, Titanium, etc. which are available in the foamed form. Besides, among them, the Aluminum Foams are commercially used in architecture and constructions due to their significant low

density and thermal conductivity, high ductility, and the competitive cost (Duarte and Oliveir, 2012)(Smith, 2012).
The mechanical characteristics of the metallic foam materials depend on their relative density and geometry (Tekoğlu et al, 2011). The study of the mechanical features is fundamental to understand the principle and behavior of the metallic foams to produce and utilize accurately. The unique combination of these particular properties proposed by metallic materials makes them special materials for various applications. Especially, those involving aluminum foam composites in sandwich panels have high capability to absorb energy, vibration, and sound, and usable in high temperature due to their great flexibility and low thermal conductivity (Kennedy, 2012) (Nosko et al, 2017).
Figure 1 shows the comparison between the potential energy absorption of the metallic foams and a fully dense elastic solid. Apparently, at the top stress level, the foams can absorb energy more than the dense solid materials. Metallic foams, in particular, aluminum foams have high strength and accordingly, they absorb energy very efficiently (Bekoz and Enver, 2013).
Three different aluminum foam samples with different densities have been tested by Banhart (1998) and the experimental results are represented in Figure 1. The foam with medium density can absorb the equal quantity of energy as others but in the lowest level of stress (Damghani and Gonabadi, 2016).

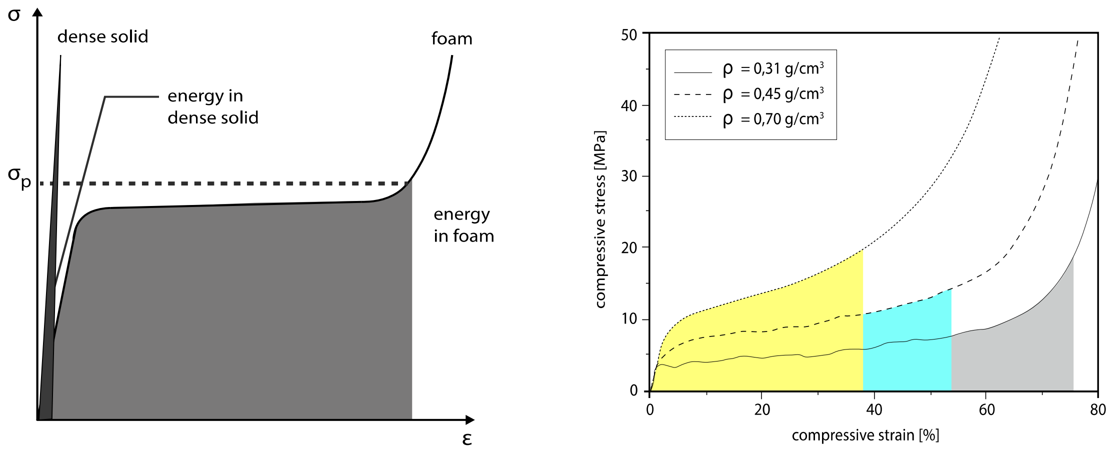

Figure 1. Left: Energy Absorption Comparison, Metallic Foam and Dense Material (Yu and Banhart, 1998). Right: Al-foams experimental test with three different density levels: 0.31 g/cm3, 0.45 g/cm3, and 0.70 g/cm3 (Yu and Banhart, 1998)

3. Potential Applications in Architecture

3.1. General Perspective of the Application

The structural and non-structural advantages of aluminum foam panels, due to the mechanical and physical properties combined with the unique appearance, result in breakthrough and limitless demands, including structural applications. There is also an increasing range of applications according to morphology, metallurgy, processing, and economy. Based on these four indexes, appropriate metal foam is found to meet the conditions of a given problem (Patel et al, 2018).

Morphology addresses the porosity openness and size scale. It is a definite point for any evaluation of the application for the closed cell foam material. Various degrees of openness, ranging from ‘very open’ to ‘completely closed’ based on the function or structural application of the material is foreseen. **Metallurgy** discusses the type of metal from which the metallic foam is manufactured. Panels with the aluminum foam core, are best applied for light-weight architecture design. Particularly, as a sandwich structure with steel cover sheets, they provide ideal properties for the building industry. While the usage of steel as a base in foam materials is more advantageous, aluminum-based foams are more applied in the building industry. Metal and alloyed foams, when loaded, show higher bending stiffness with minimized weight compared to traditional materials such as solid steel sheets or reinforced concrete decks. **Processing** is the availability of technology for the closed-cell metallic material, and the **Economy** to investigate the cost issues and the possibility of mass production in the market.

Table 2.
Advantages of the Aluminum foam core application

Application	Relevant Attributes/Properties	Structural Advantages	Architectural Advantages
Exterior, Façade, Cladding, Interior walls, Ceiling, Flooring, Stairs, Decorative purposes, Monuments, and Landscape	High bending stiffness Low weight Shield to electromagnetic waves Burning resistance Acoustic insulation Energy absorption Extreme thermal conductivity Heat dissipation Yield stress Vibration reduction 100% recyclable material Great ductility Great thermal conductivity	Minimize weight Maximize stiffness Excellent stiffness-to-weight ratio when loaded in bending High energy dissipation High mechanical damping than solid metals up to 10x	Reduce thermal conductivity Supply air transport within the material Radiation and electromagnetic protection Enhance acoustical insulation Cellular texture appearance

Recent applications of aluminum foam are wall cladding, facades, ceiling tiles, flooring, fixtures, signage, exteriors, and interiors; in slab, plate and panel formats. Existing applications in the architecture domain and the benefits in architecture and building industry utilizing are summarized in Table 2.

3.2. Applications of Aluminum Foams in Architecture

Alporas was first manufactured in the 1980s by Shinko Wire in Amagasaki, Japan. The metallic foam provided through the process called Alporas was the material's first commercialized product. Nowadays, it is using under some research centers and companies such as Foamtech in Korea and Shanxi Putai AluminumFoam Manufacturing in Linfen, China. Moreover, Architect Slawomir Kochanowicz used Alporas Al-foam for covering an office building in 2003, in Bochum, Germany. In the same year, for the international automobile exhibition in Geneva, Switzerland, a booth from Alporas foam was constructed by Kauffmann Theilig & Partners (Figure 2).

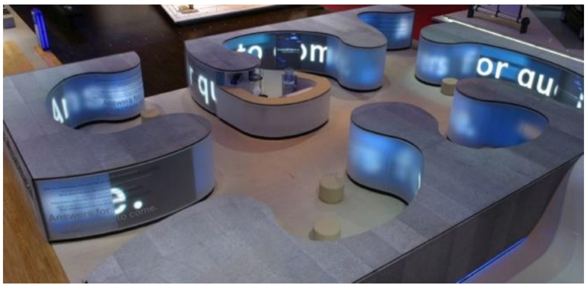

Figure 2. Kauffmann Theiling & Partners, Maybach, Daimler Chrysler, Salon de l´Automobile Geneva 2003

In the past years, Alusion Al-foam, have been applied to façade claddings. Alusion is the trade name for Cymat Stabilized Aluminum Foam and flat-panel for architectural projects. Consistently, Alusion is using as ceiling, flooring cladding or wall in both interior and exterior based on its aesthetic values and properties. Also, its products have been applied in furniture and decorative applications such as boardroom tables, reception desks, chairs, and interior feature walls. Major architectural firms such as Office for Metropolitan Architecture (OMA) have taken advantages from the material in their projects (Banhart, 2001) (Ding et al, 2013).

3.3 Case Studies

One example for the architectural application, both in interior and exterior, is Fondazione Prada by Dutch architecture firm OMA in Milan, Italy. The bubbled pattern aluminum foam cladding volume, adjacent to a fully glazed podium, creates two bulks of different qualities, demonstrating the contrast of old and new. This is remarked by the combination of gold cladding preserved building and aluminum-foam-clad new building. Interiors, on the other hand, highlight the difference by showing an act of resistance in comparison to the generic white cube of galleries.

OMA also exploited aluminum foam for the central staircase of Repossis_the Italian jewelry brand_ flagship store. The combination of the architectural and display space is the fundamental idea for designing the store, to create a whole stage. With this aim in mind, aluminum foam, as an unconventional material was used to showcase the store as an extraordinary example.

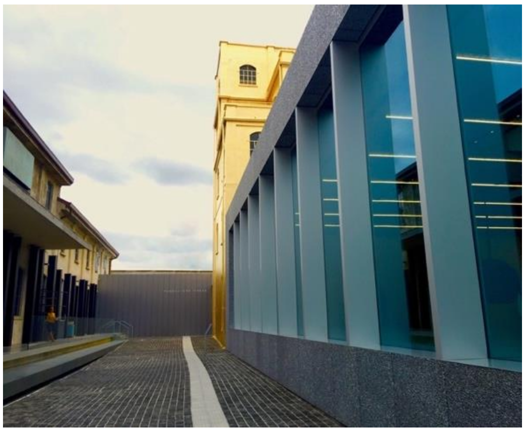

Figure 3. Left: OMA, Milan, Italy, interior and exterior cladding. Right: OMA, Paris, France, interior cladding, the steps on the lower section are made from aluminum foam

In Anenhütte cottage on heights of Alps in Ltschental, the AFS cladding carried out by Pohl in Switzerland 2015, presented an extra function by protecting the façade from the deterioration caused by weather conditions in the high altitude. In this case, the aluminum foam is not only responding to the apparent features but performing a crucial act according to its properties. The enclosure required a lightweight, stable and functional material responding to the gale-force winds, UV radiation shield, temperature variations and the unusual compressive loads from the snowstorms. Considering the criteria of energy efficiency in this human-nature interface structure, on one hand, the shape of the façade structure is fitting into the landscape on the other, and the façade is decoupled from the rest of the structure to act as thermal expansion and use thermostops.

In addition, for building elevations, Alusion foams have been used in other architectural applications (Table 3) like the translucent entrance of a souterrain, a bell tower monument part and memorial of 11 September 2001 (García-Moreno, 2016).

Other cases for architectural applications include in industrial applications. FORTEShield (AFP) provides aluminum foam panels which are highly efficient in the noise control and sound absorption together with shielding electromagnetic and damping vibration. The application ranges as a noise barrier and reverberation time controller for acoustic insulation in workshops, machinery rooms, ME rooms, construction sites, highways, acoustic chambers, pipeline silencers, and architectural spaces such as libraries, meeting rooms, theatres, studios, KTV, stadiums, train stations, FB, retail, hospitality, and etc. Particularly, its application as sound absorption performance enhances at low frequencies.

Figure 6. Lötschental, Switzerland, Cottage Anenhütte

In an extension project within a factory premise which is located about 15m away from a residential area, aluminum foam panels, weather-resistant, and lightweight were used as noise barriers. Installation and supervision of panels on a rooftop around the equipment resulted in the decline of noise levels at failed points.

Figure 7. Industrial application in a factory extension as a noise barrier

The variety of existing architecture examples, in various locations, indicate the fact that aluminum foam is a suitable material for architecture which could be applied to the elevations of buildings in different contexts, ranging from high altitudes with severe temperature variations, according to their high heat insulation characteristic. Another important feature is aesthetics. The grey, organic open and close cells and fragmented panel appearance in most case studies relevant to the design approach, create solid or translucent patterns of the buildings, and the functional applications are one of the main application group because of the fantastic thermal and electrical conductivity along with the heat dissipation of these materials that cause especial usage of them in architecture.

Table 3.
Examples of architectural applications

Architect Project Name		Location Project Year	Applications	Features and Usage
	OMA Fondazione Prada	Milan, Italy 2015	• Exterior Facade Cladding • Interior Cladding	Demonstrating contrast of old and new, by the adjacent of preserved building gold cladding and new building aluminum-foam-clad. Used as an act of resistance to the generic white cube of galleries.
	OAB Evangelical Temple	Terrassa, Spain 2010	• Facade cladding	The central volume is coated with recycled aluminum.
	Davis Brody Bond; Spacesmith EarthCam Headquarters	New Jersey 2018	• Facade cladding	Custom aluminum panels are designed, manufactured, framed, and installed to a rainscreen framing system; used to create a striking and modern look.
	Anenhütte Lötschental	Ltschental, Switzerland 2015	• Facade tiling	Endures the immense thermal and mechanical loads, weather-resistant building envelope, sensational appearance, and have a low thermal conductivity together with easier installation and transport
	hiendl_schineis architekten Entrance Structure	Augsburg, Germany 2013	• Exterior Facade Cladding • Interior Cladding	Large cells with both sides open, creating ornamentation on the surface mounted by the glass from the inside to retain the translucent, and characteristics of the foam panel
	Jaime Edis Scalpello Carillon Parroquia San Vicente de Paul, Bell Tower	Santiago, Chile	• Exterior cladding	creating a translucent and reflective front surface
	OMA Repossi Place Vendome	Paris, France 2016	• Interior cladding	The steps on the lower section are made from the aluminum foam created by injecting gas into the molten material so it becomes porous and lightweight when it cools, and sheet-metal flights connect the upper levels.

4. Conclusion

International Energy Agency is predicted 53% of the increase in terms of the energy consumption by 2027 which is due to some reasons like the dramatic increase in the population and a notable rise in industrial development. The developing countries energy demands will be more severe due to the fast building construction rate of growth (Sugimura et al., 1997). By considering the recent research, it is extensively accepted that these novel materials are making the next generation of not only the lightweight constructional and structural materials but also in the specific industries such as aerospace and military armor vehicles.

Thanks to the excellent and unique properties in architecture applications, the construction usage of metallic foams rising as in the last years. The main reason for increasing the temptation for metallic foam development is their individual mechanical properties. Ongoing developments of technology have extended production processes and manufacturing methods for a broad spectrum of cellular metals and alloys. Besides, unique properties of the material lead to a diverse range of structural advantages such as absorbing energy, high ductility, an excellent stiffness to weight ratio and non-structural advantageous like low thermal conductivity, and high vibration absorption in the various application of architecture.

Regardless of diverse aluminum foam advantageous, there are still some main challenges such as the size effect and production to have a uniform structure, to use them in different industries. Furthermore, the low-cost production of aluminum foams, compared to conventional materials, making them appropriate for mass-market applications. By considering some new recent improvement, there will be a high demand in the close future for the applications of aluminum foams in the industry and architecture (Srivastava and Sahoo, 2006).

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